read
Tit-For-Tat方法应对自私攻击
TFT机制更早期的经典方法; CoCoWa提到过
提出的基于TFT机制的ConSub方法要求消息在两个相遇节点间的等量交换，其中相遇概率和合作级别计算得到的消息效用决定了交换优先级和缓存策略。

ConSub: Incentive-Based Content Subscribing in Selfish Opportunistic Mobile Networks

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***Abstract*—Recently, content-based publish/subscribe (pub/sub) services have become a significant research field in opportunistic mobile networks (OppNets). Pub/sub is an asynchronous messaging paradigm, in which content transmissions are guided by the interest. Since selfish behavior is common in reality, nodes often behave selfishly with an aim to maximize their own utilities without considering performance of other nodes. Therefore, how to encourage nodes to collect, store and share network content efficiently is one of the key challenges under this paradigm. In this paper, we propose an incentive-based pub/sub scheme, called *ConSub*, for OppNets. In *ConSub*, Tit-For-Tat (TFT) mechanism is employed to deal with selfish behavior. *ConSub* also implements a content exchange protocol between two interacting node, thus encouraging them to play as businessmen and carry contents to satisfy each other's interest. Specifically, the exchange order is determined by the content utility, which is calculated by contact probability and cooperation level between the current node and its neighbors subscribing to the interest. Extensive realistic trace-driven simulation results show that *ConSub* is superior to existing schemes in terms of delivered packets and transmission hops with reasonable transmission cost.**

***Index Terms*—publish/subscribe, opportunistic mobile networks, selfish behavior, Tit-For-Tat**

I. Introduction

CONTENT-based networking is a novel style of communication that matches source and destination pairs based on the content [1]. Publish/subscribe (pub/sub) mechanism is a promising technology to offer content-based services in opportunistic mobile networks (OppNets) that consist of a diversity of portable devices with the capability of ad hoc wireless communication, e.g., smart phones, PDAs, and laptops [2], [3], [4]. In OppNets, end-to-end transmission path is hard to guarantee due to the time-varying network topology. Thanks to the decoupling of the binding relationship between source and destination pairs, the pub/sub mechanism has high flexibility and adaptability when dealing with dynamic network topology, which brings tremendous advantage for content dissemination in OppNets. Therefore, there is a great demand for studying such mechanism in OppNets.

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Pub/sub mechanism is an asynchronous content forwarding paradigm in which the subscribers, namely the content consumers, express their interest without knowledge of the content generators' specific ID(s) and their interest is always stable in a long period of time; and the publishers publish contents to the network without specifying the destination ID(s). Contents are organized into a set of channels, such as pop music, weather forecast, movie news and so on, while a channel is a set of labels describing a type of content [5], and nodes can subscribe to several channels. For example, at time 10:00AM, node 1 interested in job advertisement and financial news publishes song of Lady Gaga to the network. Since node 2 interested in pop music is in the communication range of node 1, and song of Lady Gaga belongs to channel pop music, node 2 can get song of Lady Gaga from node 1 directly. On the other hand, nodes out of the communication range of node 1 but still interested in this content, will have to wait until they encounter node 1 or nodes that have already had this content. In particular, at time 11:00AM, node 4 encounters node 2, which can then get song of Lady Gaga.

The above example only illustrates the situation that all nodes in the network are cooperative. However, in reality, the participants in such a network can be either cooperative or selfish, especially when network nodes are controlled by rational individuals (e.g., people and organizations) [6]. If a node is selfish, it only aims to maximize its individual utility and will not be willing to share their resources (e.g., memory space, transmission bandwidth, energy) to provide network service to others. In the worst case where every node is selfish, contents are not shared at all among mobile nodes, leading to a poor network performance. Therefore, appropriate incentive schemes in selfish OppNets need to be designed in order to stimulate cooperation between nodes and avoid extreme situations, such as defection or free riders.

Incentive schemes in selfish networks have been extensively studied, such as the Internet, mobile ad hoc networks (MANETs), and peer-to-peer (P2P) networks [7], [8]. Most existing work addressing selfishness can be classified into three categories: reputation-based [7], credit-based [8], and TFT-based approaches [9]. In this paper, we propose an incentive-based pub/sub scheme, *ConSub* (Content Subscribing), for selfish OppNets, and choose TFT as the incentive scheme. The reasons behind our choice of TFT can be listed as follows:

1) In OppNets, it is hard to provide a reliable way to detect nodes' cheating behaviors due to uncertain network connectivity. Moreover, if a selfish node is removed from the network after once being defected in cheating action, it will further waste connect opportunities between nodes in the OppNets, which are generally rare.

2) Credit-based mechanism usually requires the network to provide centralized credit bank, which is hard to achieve in intermittently-connected OppNets.
3) The TFT-based mechanism does not require the existence of trusted nodes, secure hardware or centralized credit bank. It only requires the principle of equal amounts of service when two nodes meet, which is easy to achieve in intermittently-connected OppNets.

TFT本义-等量地交换消息

Under the TFT mechanism, any pair of nodes have to offer each other equal amounts of contents while trading with each other, which means the encountered nodes can retrieve contents from each other only if they both have contents for each other. Therefore, in order to trade with others, nodes in the network have to use their resources to collect, store, and share additional contents, not meant to be consumed locally [10], [11]. Since the storage space of nodes in the network is limited, and the importance of a piece of content is different for different nodes, nodes in the network have to choose some contents which are useful for them to store. An interesting optimization problem then arises: how should nodes act in the presence of TFT towards maximizing their own revenues when the storage space is limited? The proposed scheme *ConSub* answers this question by introducing a novel content exchange protocol when two nodes are in contact. In this scheme, the exchange order is decided by the content utility, which represents the importance of a piece of content for a certain node. Intuitively, the utility of a piece of content for a certain node should depend on: *(i)* how many nodes are interested in this content, *(ii)* the contact probability to encounter these nodes in the future, *(iii)* how well-behaved these nodes are. *ConSub* captures all these features in the computation of content utility. Specifically, the content utility for a given node is calculated according to contact probability and cooperation level between the current node and its neighbors subscribing to this content, while the computation of the contact probability captures features *(i)* and *(ii)*, and the computation of the cooperation level captures feature *(iii)*. From the perspective of real life trading, the content utility can be considered as the "future trading value" for the current node to store and carry such content. Therefore, in order to get as many subscribed contents as possible, the objective of nodes in the network is to maximize the "future trading value" of the content inventory stored in their buffer.

To summarize, the novelty and contributions of this paper are as follows:

1) We propose *ConSub*, an incentive-based pub/sub scheme for selfish OppNets, in which the TFT mechanism is employed as the incentive scheme to deal with selfish behavior in OppNets.
2) In *ConSub*, a novel content exchange protocol is proposed when two nodes are in contact. Specifically, during each contact, the exchange order is decided by the content utility, and the objective of nodes in the network is to maximize the "future trading value" of the content inventory stored in their buffer.
3) Extensive realistic trace-driven simulations are conducted to evaluate the performance of our proposed scheme *ConSub*. The simulation results show that *ConSub* outperforms existing schemes in terms of delivered packets and transmission hops with reasonable transmission cost.

The remainder of this paper is organized as follows. Section II summarizes the related work. Section III proposes the incentive-based pub/sub scheme (*ConSub*) in selfish OppNets, including model and assumption (Section III-A), system architecture (Section III-B) and content exchange protocol(Section III-C). Section IV details how to compute the content utility in *ConSub*, which contains two parts: contact probability prediction (Section IV-A) and cooperation level estimation (Section IV-B). Section V evaluates the performance of *ConSub* through simulation using realistic traces. Section VI concludes the paper with direction of future research.

II. Related Work

In this section, we first introduce the related work about the content based service in OppNets, and then introduce the related work about the incentive mechanisms.

A. Content-based Service

Content-based service has been studied in the context of the Internet and traditional MANETs [12]. Generally speaking, such proposed schemes always depend on network infrastructure or stable end-to-end communication paths among (mobile) nodes. Hence, they can not be applied to the OppNets directly.

Early research on content-based service in OppNets mostly relies on existing infrastructure. TACO-DTN [13] is a related solution exploiting a hybrid architecture composed of fixed backbone and mobile devices. Specifically, TACO-DTN introduces a concept of temporal interest expressed using profiles with corresponding temporal utility for intelligent data forwarding and buffer management. Peoplenet [14] is a hybrid system that first publishes and matches information queries over infrastructure, and then uses opportunistic communication among mobile devices to forward further.

Later work on content dissemination among mobile devices without the help of infrastructure was closely related to pub/sub paradigm, in which content items are always classified into channels [15], and content dissemination is guided by users' subscriptions to the channels. Research on pub/sub paradigm in OppNets is initiated by the PodNet project [5], [16], which proposes a Podcasting architecture for opportunistic contact network environment. In the first version of PodNet [5], users only retrieve content items of channels they subscribe to. To improve the overall performance, another version [16] is proposed that designs some strategies for users to also cache other channels, although the considered strategies are simple. ContentPlace [11] aims to improve Podcasting using explicit knowledge of social networking relationships among mobile users. SocialCast [17] employs social links of participants as well, which investigates the "homophily" phenomenon, and assumes that users with common interests have more often contacts with each other. Furthermore, the cost-effectiveness of content dissemination in OppNets is investigated in [18], which proposes a general framework for pub/sub communication paradigm based on a probabilistic model of user interest without pre-defining channels.

Different from existing works on content-based service in OppNets, in our proposed scheme, *ConSub*, we consider nodes in the network to be inherently selfish rather than collaborative. This is because nodes in OppNets are controlled by rational human, who by nature often exhibits selfish nature.

B. Incentive Mechanisms

Incentive mechanisms to encourage cooperation among selfish users have also been extensively studied in the context of the Internet, MANETs and P2P networks. In general, the existing work can be classified into the following three categories.

- **Reputation based**: this category aims to detect misbehaving nodes and to isolate them from the network [7]. These approaches usually set several trusted nodes that can identify misbehavior and then banish the selfish nodes from the network. The fear of identification and punishment motivates nodes to cooperate.
- **Credit based**: in this category, nodes earn credits by helping other nodes. These credits can then be used to obtain desired service from any node in the network. However, existing credit-based protocols need either trusted centralized banks [8] or secure hardware [19].
- **TFT based**: nodes exchange good or bad behavior on the part of the peer in a TFT fashion [9]. A node fully cooperates with the neighbor if no misbehavior is detected and it correspondingly lowers service to a neighbor whose cheating is detected.

Besides the above incentive approaches for well connected wireless networks, there are also several incentive schemes recently proposed for OppNets. A novel incentive scheme proposed in [20] uses pre-existing social-network information to detect and punish selfish nodes, hence stimulating them to participate in the network. The pre-existing social-network information obtains through interview, or from an online social network (e.g., Facebook friends lists). A reputation-assisted data forwarding protocol proposed in [21], [22] integrates the reputation framework with a bare-bone data forwarding protocol. An incentive-aware routing protocol in OppNets was proposed in [6], aiming to adaptively optimize individual performance subject to TFT without significant degradation of system-wide performance. In [23], a credit-based incentive scheme was proposed to deal with selfish behavior in OppNets. This work incorporates an incentive scheme into data dissemination in selfish OppNets with multiple interest types. In [24], an incentive data collaboration schemes was proposed to encourage user participation of selfish nodes in OppNets, however this work does not take into consideration the resource constraints like buffers. A similar work was presented in [10], which proposes a utility driven trading system, called MobiTrade, to optimize the content sharing strategy in OppNets, and derives an optimal policy to split the buffer of a node in zones allocated to each channel. This work also chooses TFT as the incentive mechanism to deal with selfish behavior in OppNets, however it does not take the Time-to-Live (TTL) of contents into consideration. Indeed, the TTL has significant impact on the content utility. If TTL of a piece of content is going to expire, the contact probability to meet those nodes subscribing to this content will be low; hence the utility of this content will also be low.

Different from the above works, our proposed incentive-based pub/sub scheme, *ConSub*, takes both the TTL of contents and the buffer into consideration, and proposes a novel content exchange protocol when two nodes are in contact.

III. Proposed Scheme *ConSub*

This section first gives a brief introduction to the network model, the interest and content model and several assumptions in our proposed scheme. Next we introduce the system architecture and content exchange protocol between nodes of the incentive-based pub/sub scheme in selfish network.

A. Models and Assumptions

1) Network Model: In OppNets, the nodes' contact in the network can be described as a graph $G(V, E)$. The random contact process between nodes i and j can be modeled as $e_{ij} \in E$, where $i, j \in V$. Some recent studies [25], [26] found that the pair-wise node inter-contact time in realistic traces follows an exponential distribution. Specifically, the authors in [25] conduct χ^2 hypothesis test on each contacted node pair in the *Infocom 06* [27] and *MIT Reality* [28] traces, to test whether "the pair-wise node inter-contact time follows an exponential distribution". Their results demonstrate that when enough number of test intervals ($\geq$ 10) is used, over 85% of the contacted node pairs in the above traces pass the test. Based on these results, we also assume that the distribution of pair-wise node inter-contact time in OppNets follows the exponential distribution. Thus the contact between two nodes i and j becomes a homogeneous Poisson process with contact frequency of λ_{ij}, which is calculated by time average.

2) Interest and Content Model: Nodes in the network need to express their interests towards different (kinds of) contents in a certain way and accordingly subscribe to those interesting contents. They may have one or multiple interests and can subscribe to several channels. Identifying the contents of those channels is based on the matching between the key words of subscription and the description of the channel, usually in the form of key words. The matching model for these key words is suitable to pub/sub communication model discussed in this paper, because nodes in the network may have no idea what
不知道找什么 对能匹配上的感兴趣
they are looking for or have interest in the contents which match some key words (such as pop music, weather forecast, movie news, and so on). Since this paper focuses on introducing incentive-based pub/sub mechanism into selfish network environment, we do not consider the detailed matching process of interest and content. For similarity, we assume the total number of channels in the network is K and each content subscribed by nodes in the network can only be described by one channel. At the network start time, every node publishes its channel messages it is interested in to its neighbors. Thus every node in the network will collect channel messages of interest from its neighbors and form a list of such channels.

In OppNets, each node can be the content subscriber or the content publisher. Each published content includes

(d, k, T_d, TTL), while d is the sequence number of the content, k is the sequence number of the associated channel, T_d is the generation time of the content, and TTL is the valid time of the content, which includes several units of time.

3) Assumptions: For simplicity, we assume that clock (time) in the network is synchronous, and the cache size of nodes in the network is equal to B. We also assume that the content generated in the network has the same volume capacity; thus when nodes exchange contents, we can count the total volume of the content by counting the number of packets. At last, we assume that the contact duration between pair-wise nodes is long enough to complete the content exchange.

B. The *ConSub* Architecture

The architecture of *ConSub*, the incentive-based pub/sub scheme in selfish OppNets proposed in this paper includes the following three parts:

1) Interest Channel Manager: Each node's interest channel management station keeps the interest channel information subscribed by its one-hop neighbors and merges it with its own interest channels to form a list of interest channels. Let the set of node i's one-hop neighbors be $\mathcal{N}_i$, among which $\mathcal{N}_i^k$ is the subset of its one-hop neighbors interested in channel k. Furthermore, node i keeps the pair-wise inter-contact time with all its one-hop neighbors in $\mathcal{N}_i$.

效用 是否值得保存在本地

2) Content Utility Estimator: We assume that all nodes in the network bid equal for each content when they are trading. Without loss of generality, we set all the biding prices as "1". So we can measure statistics by counting the number of packets, which is also conformed to the TFT exchange principle. Under the TFT mechanism, if nodes want to get subscribed contents, they have to provide equal units of contents back to the counterpart. Therefore, in order to trade with others, nodes in the network have to store some contents in their buffer. However, since the importance of a piece of content is different for different nodes, and the size of their buffer is limited, nodes have to choose some contents which are useful for them to store. Therefore, we have first to calculate the utility of contents for different nodes. From the perspective of content trading, the utility of a piece of content in channel k for node i is the sum of the contact probability $Pr_{ij}(T)$ between node i and its neighbors which are interested in this content within the remaining valid time T of this content, and the computing method detailed in Section IV-A. From the perspective of cooperation, the willingness that node i gives service to each neighbor is different. Specifically, taking two nodes i and j as an example, if j behaved well in the past trading process with i, or the transaction between them in the past was large and stable, then node i will give priority to storing contents which j is interested in. This is because i can do more trading with j if node i chooses to store contents which j is interested in. Hence, we propose the cooperation level ω_{ij} based on the transaction between nodes i and j in the past, and the computing method will be introduced in Section IV-B. Taking these two parameters into consideration, the utility of a content d in channel k for node i is defined as:

TFT 想要获得所订阅的content 需要提供等量的content

遇到对这个内容感兴趣的邻居的概率 Pr
以往交易的稳定性 w

$$U_i^k(d) = \sum_{j \in \mathcal{N}_i^k} \omega_{ij} Pr_{ij}(T), \quad (1)$$

where $\mathcal{N}_i^k$ is the set of node i's one-hop neighbors whose interest contains channel k in the range of $[1, K]$; and T is the remaining valid time of content d, which can be calculated by using the current time, the generation time T_d and TTL.

3) Buffer Manager: Since the importance of a piece of content is different for different nodes, and the size of the buffer is limited, nodes in the network have to choose some useful contents to store. Therefore, in order to get as many subscribed contents as possible, the objective of nodes in the network is to maximize the expected content utility in their buffer, which can be expressed as:

内存管理：以最大化sum(效用值)的增加量 为目标

$$Max \;\; U_i = \sum_{k=1}^{K} \Big(\sum_{d \in \theta(k)} U_i^k(d) - \sum_{d \in \phi(k)} U_i^k(d) \Big), \quad (2)$$

where U_i is the utility function of node i; K is the total number of channels; and $\theta(k)$ and $\phi(k)$ are the set of contents belonging to channel k in their buffer after and before exchange, respectively.

The cache management of a node is mainly based on the content utility. When new contents are sent to the current node, it places the contents into the buffer corresponding to their content utility. If the buffer size of the current node is full, the contents with higher utility can seize the cache position that are occupied by the contents with lower utility. Note that the expired contents will be deleted directly from the cache management station, even if there is unoccupied space.

超时的content去掉，高utility的content抢占cache位置

C. The Content Exchange Protocol

Based on above definitions, models and assumptions, our proposed incentive-based pub/sub scheme is outlined below. Consider two nodes i and j as an example. When i meets j, node i needs to decide whether or not to exchange contents in its buffer with the latter. If j has some useful contents in its buffer for i, for example, some contents which are subscribed by i, or some contents which can increase the content utility in i's buffer, then i will choose to exchange contents with j. Due to selfish nature, node i will give priority to getting its subscribed contents, and then aims to get contents which can maximize its own expected content utility in its buffer. After obtaining a subscribed content by trading with j, node i will consume this content directly without storing in its buffer. To facilitate our discussions, we assume that each content, say d at node i, is associated with a metadata, which includes its sequence number (d), associated channel (i.e., k), generation time (T_d) and TTL. Let L_i denote the set of metadata of contents stored at node i. Then the proposed incentive-based pub/sub scheme, *ConSub*, in selfish OppNets works as follows in six steps:

1) When node i meets j, then i first sends a control message to j, which includes the interest channel list (including that of itself and its neighbors) and the set L_i. Node j also sends a similar control message to i.
2) When i receives the control message from j, it first creates a set S_i to denote the set of contents that are

i向其他节点通知，j已经受到免费content了。
如果j一直不帮忙存储content，则j的合作level一直为0。相关的效用就小

available at j but not at i, i.e., $S_i = L_j - (L_i \cap L_j)$. Similarly, node j creates a set S_j.

匹配上对端节点的兴趣；类似于到达目的的消息 先传

3) Node i checks if there are any contents in S_i matching its interest. Let $\overline{S_i}$ denote the set of such contents. Then node i adds them into the candidate request content list R_i with high priority. Accordingly, node j does so in a similar way and obtains the candidate request content list R_j.
4) After determining the contents matching their interest, nodes i and j next decide the contents not matching their interest, on the basis of maximizing the total content utility in their buffer. Let P_i denote the set of contents in S_i that does not include contents matching its interest, i.e., $P_i = S_i - \overline{S_i}$. Then i computes the content utility for all items in P_i and the existing contents in its own buffer. In the decreasing order of content utility, i adds the first X_i contents under the constraint of buffer size B (i.e., chooses all contents when the buffer is not full) into the candidate request content list R_i with low priority. Accordingly, node j does so in a similar way.
5) Node i then selects the items coming from the set S_i in the candidate request content list R_i, and orders them in the decreasing order of priority and content utility into the request content list and sends the request list back to j. Node j does so in a similar way.

两边请求同样数量的消息,
但是只传min(X,Y)

6) Suppose nodes i and j request X and Y contents from each other, respectively. Under the constraint of TFT, they both send each other the first $min(X, Y)$ contents in the request content list. If i receives contents requested from j, it first consumes its subscribed contents locally, and then places other contents into the buffer corresponding to their content utility. When the buffer is full, new contents with higher utility will remove the old contents with lower utility from the buffer. As mentioned above, the node's buffer is managed by the content utility. Node j carries the same actions.

Note that at the beginning of the protocol, only few nodes (i.e., the publisher) will have some contents in their buffer while others (likely the vast majority) will have no content in their buffer. Therefore, it would be impossible for the latter to receive any contents from others under the constraint of TFT. To deal with this issue, in BitTorrent [29], a P2P file sharing protocol used for distributing large amounts of data over the Internet, new nodes can get some free contents at startup to get them started. In this paper, a similar approach is applied here. When new nodes enter the network, we allow them to get some free contents from other nodes, and the free content quota is set as V, a small number. We believe this approach can improve the robustness of our proposed scheme and allow it to scale to large networks.

初始时候，少部分node有content，大部分node没有content,没法交换

补一些免费的content 使得大家都可以交换

While entering the network, new nodes can get some free contents from other nodes. Hence, some selfish nodes may have the incentive to leave the network immediately, and join again to get the free content quota after they use up the free content quota. This process introduces another popular incentive issue called "free riders" into the network. To protect against such "free riders", the following steps are taken. First, when two nodes (say i and j) meet, they check if they have enough contents in their buffer for trading. For example, if i finds that the number of contents in j's buffer is larger than the free content quota V, then j cannot get free contents from i. Second, if j does not use its buffer to store contents for other nodes, the number of contents in j's buffer will be always less than the free content quota V, then j can always get free contents from other nodes. To avoid this situation, nodes in the network send control messages. For example, if j gets $v < V$ contents from i, then i will send control messages to notify j's other neighbors that j has got v free contents from it. If the total number of free contents received from its neighbors is larger than V, then j cannot get free contents from other nodes any more. Finally, if node j just gets free contents from its neighbors without giving anything back to the network, its cooperation level with its neighbors will be zero. Then, j's neighbors will not store contents which are subscribed by j in their buffer, which makes it difficult for j to get subscribed contents from its neighbors. Therefore, selfish nodes now have the incentive to provide contents for other nodes.

IV. Computing Content Utility

For node i, the utility of contents in channel k depends on contact probability and cooperation level between node i and its neighbors subscribing to this channel. This section describes how to estimate these two indicators and give the computing method of the content utility.

A. Contact Probability Prediction

We assume that the random variable $X_{ij}(t)$ denotes the cumulative number of contacts between nodes i and j at time t and any two contacts between them are independent from each other. Hence, $X_{ij}(t)$ is a stochastic process with independent increments. That is, for any $0 \le t_1 < t_2 < \ldots < t_n$, $X_{ij}(t_2) - X_{ij}(t_1), X_{ij}(t_3) - X_{ij}(t_2), \ldots, X_{ij}(t_n) - X_{ij}(t_{n-1})$ are all independent random variables. As introduced in Section III-A, some recent studies [25], [26] found that the pair-wise node inter-contact time in realistic traces follows an exponential distribution, which we also assume in this paper. The contact frequency λ_{ij} between nodes i and j is indicated by the contact rate, and can be computed by the following time average method:

$$\lambda_{ij} = \frac{n}{\Sigma_{l=1}^{n} T_{ij}^{l}}, \tag{3}$$

where $T_{ij}^1, T_{ij}^2, \ldots, T_{ij}^n$ are inter-contact time samples between nodes i and j.

Thus, $X_{ij}(t)$ can be modeled as a homogeneous Poisson process. For any $t > 0$, the number of contacts $X_{ij}(t + \Delta t) - X_{ij}(t)$ between nodes i and j within time Δt follows the Poisson distribution, which can be expressed as:

$$Pr(X_{ij}(t + \Delta t) - X_{ij}(t) = k) = \frac{(\lambda_{ij}\Delta t)^k e^{-\lambda_{ij}\Delta t}}{k!}. \tag{4}$$

Then, the contact probability between nodes i and j within time T can be expressed as:

$$Pr_{ij}(T) = 1 - e^{-\lambda_{ij}T}. \tag{5}$$

B. Cooperation Level Estimation

We assume that the cooperation level between nodes i and j is $\omega_{ij} \in [0,\ 1]$, where 0 represents no cooperation and 1 represents full cooperation. When setting the cooperation level ω_{ij} between nodes i and j, the mean μ_{ij} and standard deviation δ_{ij} of the contents exchanged in the past should be mainly considered. Therefore, the cooperation level ω_{ij} between nodes i and j can be calculated as follows:

$$\omega_{ij} = \alpha\ e^{\mu_{ij}-1} + (1-\alpha)\ e^{-\delta_{ij}}, \tag{6}$$

where the mean μ_{ij} is used to measure the average amount of contents exchanged every time nodes i and j meet, and the cooperation level ω_{ij} increases as μ_{ij} increases. On the other hand, the standard deviation δ_{ij} is used to measure the stability of past trading between nodes i and j, and the cooperation level ω_{ij} decreases as δ_{ij} increases. Therefore, according to the definition of content utility, node i will give priority to storing contents which j is interested in when the past transaction between them was large and stable. In Equation (6), α is in the range of [0, 1]; here α and $1-\alpha$ represent the weight of the mean and standard deviation respectively, which will be assigned different values according to the scenarios. In order to set the cooperation level ω_{ij} in the range of [0, 1], we choose the nodes' cache size B as the denominator of the equation. Thus, μ_{ij} can be calculated as follows:

$$\begin{aligned}\mu_{ij} &= \frac{\frac{C_1}{B} + \frac{C_2}{B} + \ldots + \frac{C_n}{B}}{n} \\ &= \frac{\Sigma_{l=1}^{n} C_l}{n \cdot B}\ ,\end{aligned} \tag{7}$$

where C_l stands for the amount of contents exchanged between nodes i and j at the lth contact.

Moreover, δ_{ij} can be calculated as:

$$\begin{aligned}\delta_{ij} &= \frac{\frac{|C_1-\overline{C}|}{B} + \frac{|C_2-\overline{C}|}{B} + \ldots + \frac{|C_n-\overline{C}|}{B}}{n} \\ &= \frac{\Sigma_{l=1}^{n} \mid C_l - \overline{C} \mid}{n \cdot B},\end{aligned} \tag{8}$$

where $\overline{c}$ is the average amount of contents exchanged between i and j in the past lth contacts, which can be calculated as $\frac{\Sigma_{l=1}^{n} C_l}{n}$.

When we substitute Eq. (5) together with Eq. (6) into Eq. (9), we can compute the content utility $U_i^k(d)$ of content d in channel k for node i as follows:

$$U_i^k(d) = \sum_{j \in \mathcal{N}_i^k} (\alpha\ e^{\mu_{ij}-1} + (1-\alpha)\ e^{-\delta_{ij}})(1 - e^{-\lambda_{ij}T}). \tag{9}$$

V. Performance Evaluation

In this section, we evaluate the performance of our proposed scheme, *ConSub*, in selfish OppNets. Specifically, we compare it with the following four content pub/sub schemes:

1) **Ad hoc Podcasting (referred to as Podcasting)** [16]: nodes receive all contents which their neighbors feel interested in, and randomly discard contents when their buffer is full.
2) **Random Epidemic Forwarding (referred to as RanForwd)**: nodes randomly receive contents which their neighbors are interested in, and randomly discard contents when their buffer is full.
3) **ContentPlace** [11]: nodes receive all contents which their neighbors feel interested in, and discard contents with low utility when their buffer is full. The content utility is calculated by Most Frequently Visited (MFV) policy.
4) **MobiTrade** [10]: each node defines a buffer quota for each channel based on the past reward of the channel. If the amount of contents in channel k is less than the buffer quota for channel k, or if there is enough free space in the buffer, then a node will receive contents in this channel. However, if the amount of contents in channel k is larger than the buffer quota for channel k, and the buffer is full, then a node will receive contents in this channel and discard the oldest contents belonging to the channel which exceeds the largest buffer quota.

TABLE I
Basic statistics of the traces

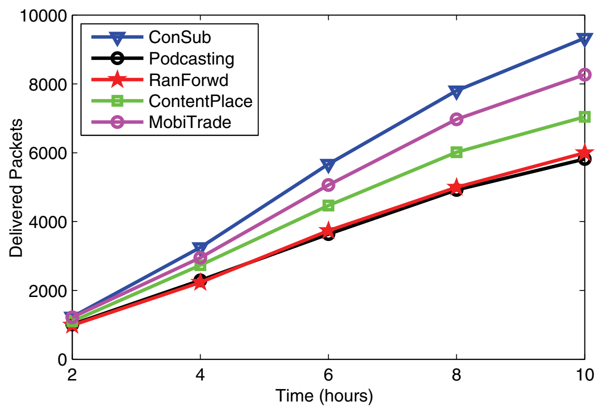
Trace	*MIT Reality*	*Infocom 06*
Device	Smart Phones	iMote
Network type	Bluetooth	Bluetooth
No. of internal contacts	114,046	182,951
Duration (days)	246	3
Granularity (seconds)	300	120
No. of devices	97	78
Contact frequency/pair/day	0.024	6.7

We use two experimental traces, *Infocom 06* [27] and *MIT Reality* [28] collected from realistic environments to evaluate the performance of the above schemes. Users in these two traces carry bluetooth-enabled mobile devices, which record contacts by periodically detecting their peers nearby. The traces cover various types of corporate environments and have various experimental periods. The detail of the traces is summarized in Table I.

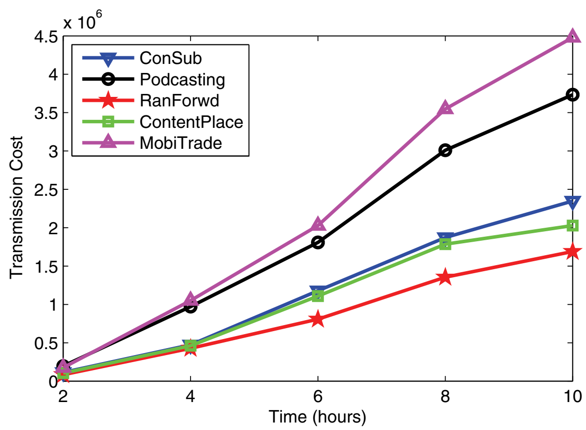
A. Simulation Setup

We use part of the traces (the first day of *Infocom 06*, and September and October of *MIT Reality*) to model and characterize user mobility (i.e., calculate contact rate λ_{ij} and the probability of next visiting community for *ConSub* and ContentPlace, respectively). We use another part of the traces (the second day of *Infocom 06*, and November of *MIT Reality*) to evaluate the performance of the selected schemes. In particular, unless otherwise stated, there are 5 interest channels in the network, and each node only expresses interest in randomly one channel; the cooperation level parameter $\alpha = 0.8$ and $V = 3$. During the whole experiment, we consider that each node generates contents that match one of the channels, and the packet generation rate follows a uniform distribution, while 1 packet/hour means nodes generate 1 content per hour. The size of all contents equals to $40K$, each has the same TTL in all experiments. Finally, the buffer size of a node $B = 1000K$.

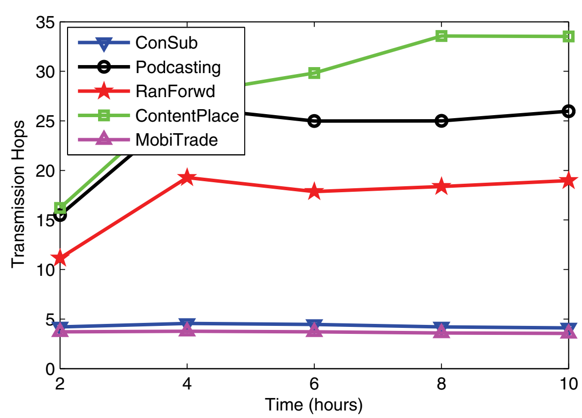
Our goal is to disseminate contents to corresponding interested nodes with as low both delay and traffic overhead as possible. In our simulation studies, we focus on the following three performance metrics for performance evaluation:



(a) Delivered packets

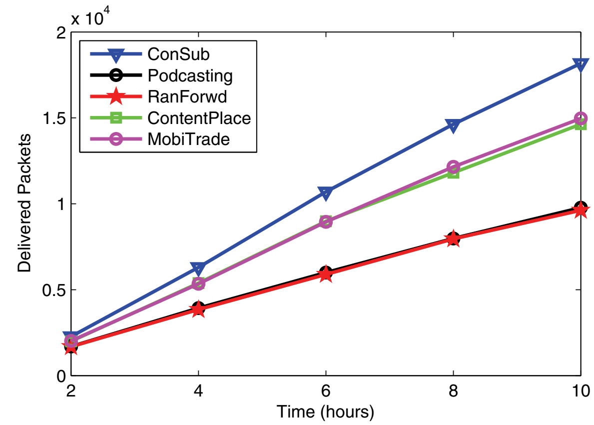


(b) Transmission Cost

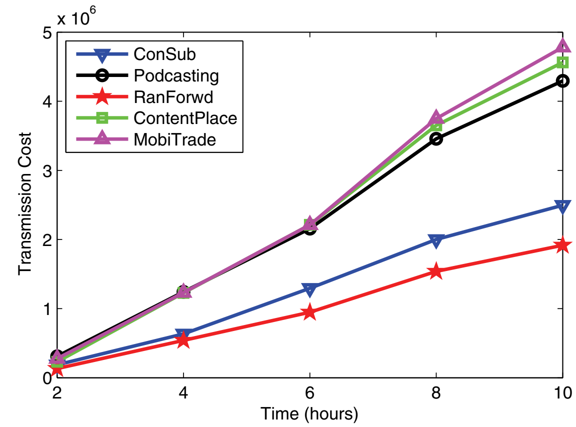


(c) Transmission Hops

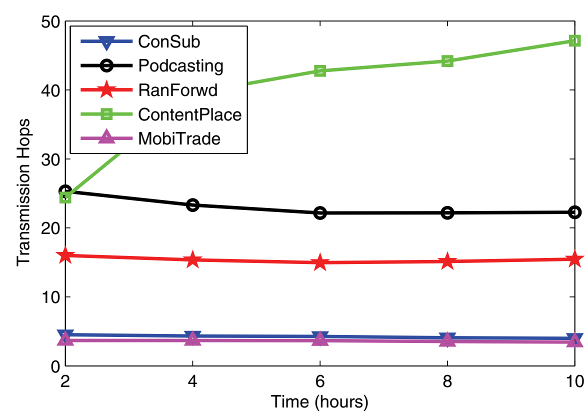
Fig. 1. Performance comparison of *ConSub* with other schemes when packet generation rate is 1 packet/hour



(a) Delivered packets



(b) Transmission Cost



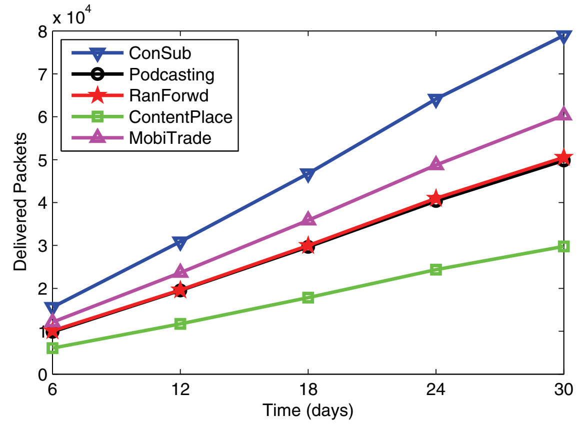
(c) Transmission Hops

Fig. 2. Performance comparison of *ConSub* with other schemes when packet generation rate is 2 packets/hour

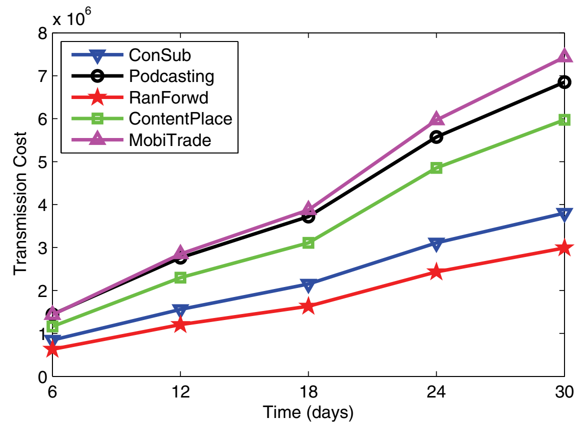
1) **Delivered Packets**: the total number of packets successfully delivered for channels subscribed by nodes in the network, which reflects the effectiveness of the scheme.
2) **Transmission Cost**: the total number of packets exchanged by nodes in the network, which reflects the energy consumption of the scheme.
3) **Transmission Hops**: the average transmission hops of successfully delivered packets. The smaller this metric, the more rapid is the delivery of the content to its subscriber.

B. Performance Comparison

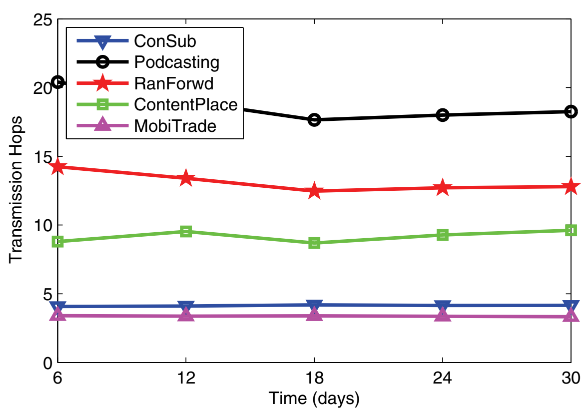
We use the *Infocom 06* trace to carry out experiments with different packet generation rates (1 packet/hour and 2 packets/hour), and use the *MIT Reality* trace to do experiments with different TTL values (24 hours and 48 hours). The goal is to compare the performance of our proposed scheme, *ConSub*, with other existing schemes with different datasets and check the impact of the changing metrics on the performance of different schemes. Then we use the *Infocom 06* trace to carry out experiments with different values of the cooperation level



(a) Delivered packets

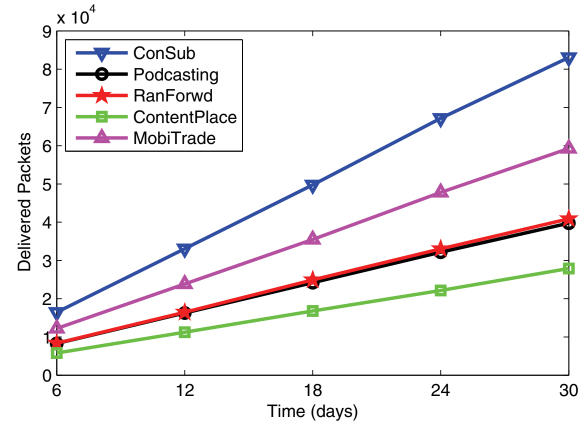


(b) Transmission Cost

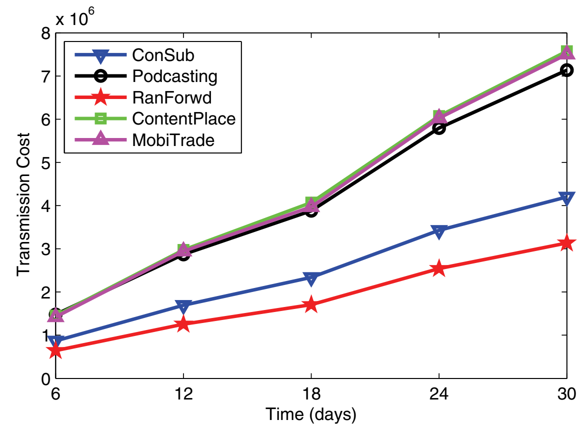


(c) Transmission Hops

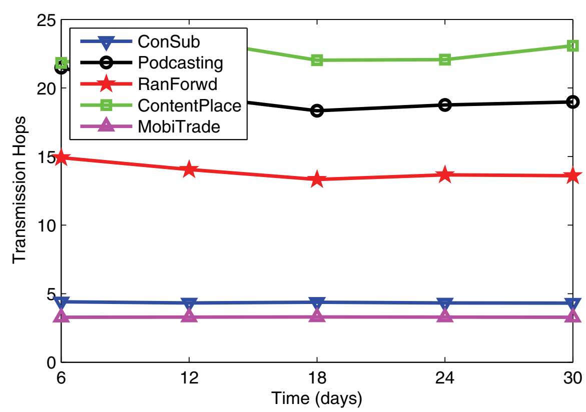
Fig. 3. Performance comparison of *ConSub* with other schemes when TTL is 24 hours



(a) Delivered packets



(b) Transmission Cost



(c) Transmission Hops

Fig. 4. Performance comparison of *ConSub* with other schemes when TTL is 48 hours

parameter α (α = 0.8, 0.9 and 1.0), and with different interest channels (namely 5, 20 and 40 interest channels), aiming to check the impact of the changing metrics on the performance of our proposed scheme.

1) Different packet generation rates: For fixed node buffer and packet sizes, increased packet generation rate leads to more contents published in the network as well as heavier traffic. Under this situation, it is more challenging for the scheme to store right contents and discard others when the traffic in the network becomes heavy. Therefore, in this part, we use the *Infocom 06* trace, and change the packet generation rate from 1 packet/hour to 2 packets/hour to investigate how it influences the *ConSub* and other existing schemes.

From Figs. 1 and 2, we observe that *ConSub* and MobiTrade outperform other schemes in terms of delivered packets and transmission hops, implying they can deliver more packets in less time. The is because *ConSub* and MobiTrade take buffer management into consideration and aim to store contents with higher utility into their buffer. *ConSub* performs better than MobiTrade in terms of delivered packets and transmission cost, while the transmission hops of *Consub* is nearly the same as MobiTrade. Therefore, *ConSub* outperforms MobiTrade in

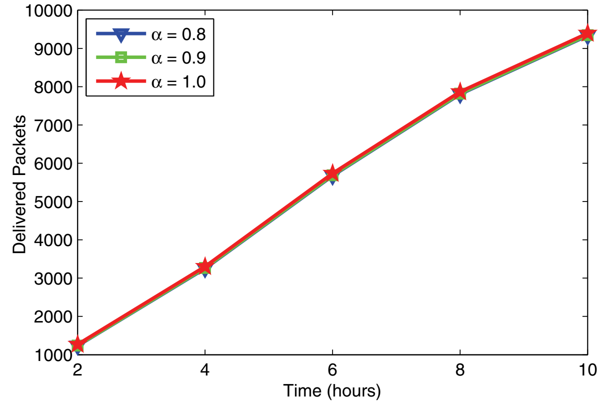
Infocom 06 trace when the packet generation rate increases. This is because *ConSub* considers the TTL of contents into consideration to calculate the content utility. Indeed, the TTL has significant impact on the content utility. If TTL of a piece of content is going to expire, the contact probability to meet nodes subscribing to this content will be low; hence the utility of this content will also be low. Therefore, nodes can more efficiently manage their buffer in *ConSub*. At the same time, the transmission cost of *ConSub* is nearly half of Podcasting and ContentPlace schemes, and only slightly larger than RanForwd. Thus, it can be concluded that *ConSub* is a high-efficiency scheme when evaluating with the *Infocom 06* trace. ContentPlace also takes the buffer management into consideration, but it performs worse than *ConSub* and MobiTrade. The main reason is that the content utility of ContentPlace is calculated by the Most Frequently Visited (MFV) policy, which only considers the contact probability to meet subscribed nodes in those most frequently visited communities in the future. The delivered packets of RanForwd and Podcasting perform worst. The main reason is that they do not take the buffer management into consideration.

When the packet generation rate changes from 1 packet/hour to 2 packets/hour, the delivered packets in different schemes all increases, and *ConSub* performs the best. The transmission cost and hops of *ConSub* nearly keep the same, while those of the other schemes increase notably. Specifically, the transmission cost and hops of ContentPlace increase most obviously when the traffic becomes heavy in the network. Therefore, we conclude that *ConSub* is an effective and robust pub/sub scheme in selfish OppNets.

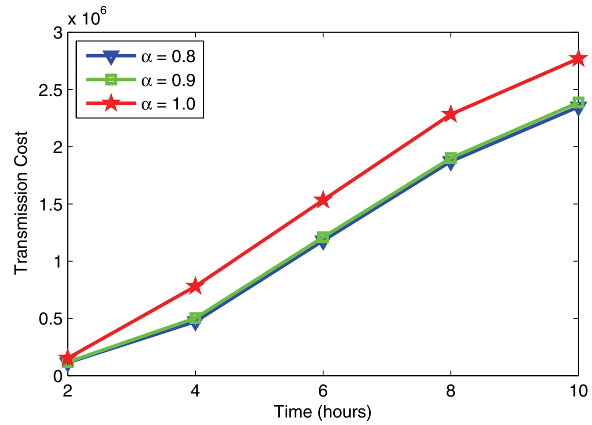
2) Different TTL: Compared with the *Infocom 06* trace, the opportunistic contacts among (mobile) nodes in the *MIT Reality* trace is infrequent. When other settings are fixed and the TTL increases, the contents have more opportunities to be delivered to the subscribed nodes, but they also add to the traffic in the network. Therefore, in this part, we use the *MIT Reality* trace, and change the TTL from 24 hours to 48 hours to investigate how it influences *ConSub* and other existing schemes.

From Figs. 3 and 4, we observe that *ConSub* and MobiTrade again outperform other schemes in terms of the delivered packets and transmission hops. *ConSub* still outperforms MobiTrade in terms of delivered packets and transmission cost, while the transmission hops of *ConSub* is only slightly larger than MobiTrade. Therefore, *ConSub* still outperforms MobiTrade in the *MIT Reality* trace when the TTL increases. It is worth mentioning that ContentPlace with *MIT Reality* trace does not behave as good as with *Infocom 06* trace. Although the transmission cost and hops are large, ContentPlace delivers the least successful packets. The main reason may be that the communities in *MIT Reality* are not as obvious as in the *Infocom 06*, hence ContentPlace cannot choose appropriate contents to store, which decreases the effectiveness of ContentPlace. At the same time, the transmission cost of *ConSub* is nearly half of Podcasting and ContentPlace, and only slightly larger than RanForwd. This implies that *ConSub* is highly efficient in both *MIT Reality* and *Infocom 06* traces.

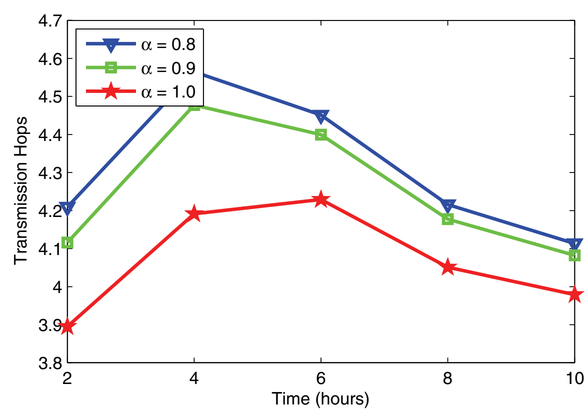
In summary, as the TTL increases, only the delivered packets of *ConSub* increases significantly, while other schemes are influenced badly by the heavy traffic. Therefore, our proposed scheme, *ConSub*, outperforms other schemes when the TTL increases in the *MIT Reality* trace.



(a) Delivered packets



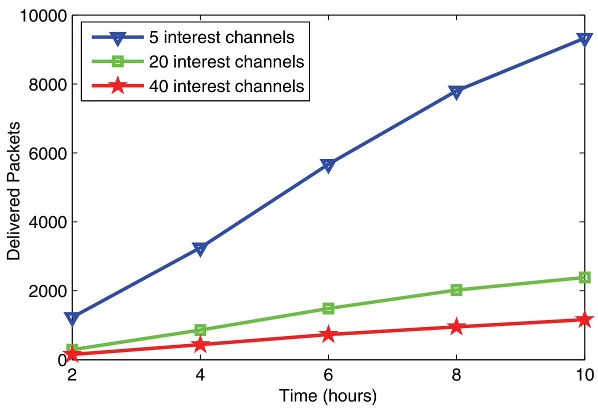
(b) Transmission Cost



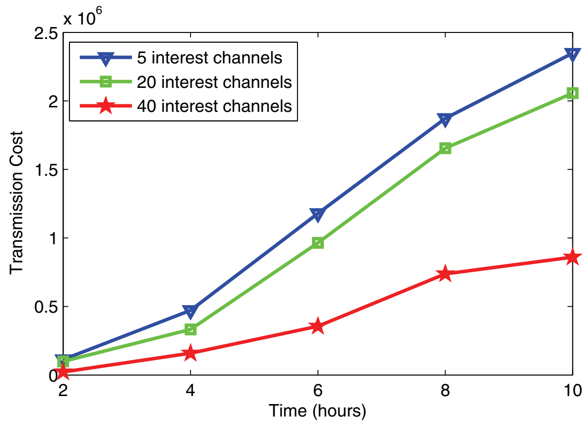
(c) Transmission Hops

Fig. 5. Performance of *ConSub* with varying cooperation level

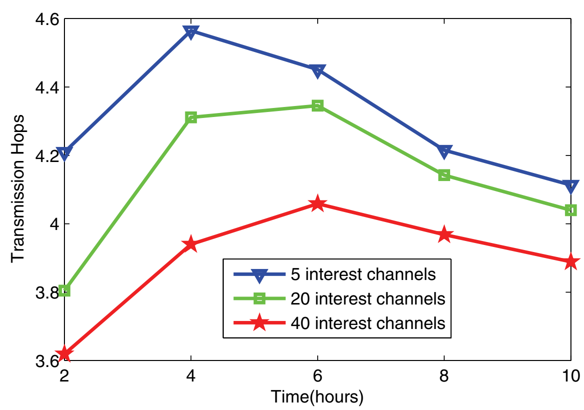
3) Different cooperation level parameter α: Cooperation level plays an important role in the application and performance of *ConSub*. The value of cooperation level is determined by its parameter α. For large α, each node is apt to exchange contents with its neighbors who perform well in the past average amount of exchanged contents. As a result, in this part, we use the *Infocom 06* trace, and change α from 0.8 to 1.0 to investigate how it influences *ConSub*.



(a) Delivered packets



(b) Transmission Cost



(c) Transmission Hops

Fig. 6. Performance of *ConSub* with varying number of interest channels

From Fig. 5, as α increases from 0.8 to 0.9, the delivered packets, transmission cost and transmission hops nearly remain the same. However, when α increases from 0.9 to 1, the delivered packets remains the same, while the transmission cost increases significantly, and the transmission hops decreases a lot. A reasonable explanation is that when α increases from 0.8 to 0.9, the cooperation level is not only impacted by the past average amount of exchanged contents, but also by the standard deviation of exchanged contents. Therefore, it is difficult for nodes in the network to choose contents with higher utility for exchange. However, when α increases from 0.9 to 1, the cooperation level is only influenced by the past average amount of exchanged contents, and it is easier for nodes in the network to choose contents which have higher contents utility for exchange.

To summarize, as α increases from 0.8 and 0.9, the performance of *ConSub* is nearly the same. However, when α increases from 0.9 to 1, the transmission cost increases, and the transmission hops decreases, which changes the balance point between the transmission cost and transmission hops. Therefore, the value of α should be chosen with the consideration of the performance requirement of the network.

4) Different interest channels: In realistic environments, the number of interest channels always changes with different applications. Hence, it is important to test the performance of *ConSub* with different interest channels. We add two test cases: with 20 and 40 interest channels. In these two cases, each node also expresses interest in one channel. We use the *Infocom 06* trace to evaluate the performance of *ConSub* in different test cases.

From Fig. 6, as the number of interest channels increases, the delivered packets, transmission cost and transmission hops all decrease. A reasonable explanation is that it is hard for nodes in the network to choose contents with higher utility for exchange when the number of interest channels increases. Therefore, nodes will exchange less amount of contents with others, which causes the decrease of the delivered packets, transmission cost and transmission hops.

Therefore, the number of interest channels has significant impact on the performance of *ConSub*. If the number of interest channels is too large, it will obviously decrease the performance of *ConSub*, thus we should choose an appropriate number of interest channels according to different applications.

VI. Conclusion

In this paper, we investigated the content pub/sub scheme in OppNets. Considering the selfish behavior of nodes, we propose an incentive-based pub/sub scheme, called *ConSub*, for selfish OppNets. In *ConSub*, we choose the TFT mechanism as the incentive scheme to deal with selfish behavior. Moreover, in order to encourage nodes in the network to play as businessmen and carry contents to satisfy each other's interest, we also propose a novel content exchange protocol when two nodes are in contact. Specifically, the exchange order is decided by the content utility, and the objective of nodes in the network is to maximize the utility of the content inventory stored in their buffer. Extensive realistic trace-driven simulation results show that *ConSub* is superior to other existing schemes in terms of delivered packets and transmission hops with reasonable transmission cost. In the future, we will perform simulations on the detailed matching process of subscription and contents in *Consub*. Moreover, since contents in our scheme are stored according to their content utility, if the buffer size is very large, it will increase the storage and computation complexity. Therefore, in the future, we will take such complexity into consideration.

References

[1] P. Marshall, "From self-forming mobile networks to self-forming mobile content services," *ACM Mobicom Keynote Speech*, 2008.

[2] J. Fan, J. Chen, Y. Du, P. Wang, and Y. Sun, "Delque: A socially-aware delegation query scheme in delay tolerant networks," *IEEE Transactions on Vehicular Technology*, no. 99, pp. 2181–2193, 2011.

[3] J. Fan, Y. Du, W. Gao, J. Chen, and Y. Sun, "Geography-aware active data dissemination in mobile social networks," in *Proceedings of IEEE MASS*, 2010.

[4] H. Zhou, H. Zhao, and J. Chen, "Energy saving and network connectivity tradeoff in opportunistic mobile networks," in *Proceedings of IEEE Globecom*, 2012.

[5] V. Lenders, G. Karlsson, and M. May, "Wireless ad hoc podcasting," in *Proceedings of IEEE SECON*, 2007.

[6] U. Shevade, H. H. Song, L. Qiu, and Y. Zhang, "Incentive-aware routing in dtns," in *Proceedings of IEEE ICNP*, 2008.

[7] R. Mahajan, M. Rodrig, and D. W. J. Zahorjan, "Sustaining cooperation in multi-hop wireless networks," in *Proceedings of USENIX NSDI*, 2005.

[8] S. Zhong, J. Chen, and Y. R. Yang, "Sprite: A simple, cheat-proof, credit-based system for mobile ad-hoc networks," in *Proceedings of IEEE INFOCOM*, 2003.

[9] F. Milan, J. J. Jaramillo, and R. Srikant, "Achieving cooperation in multihop wireless networks of selfish nodes," in *Proceeding of the workshop on Game theory for communications and networks*, 2006.

[10] A. Krifa, C. Barakat, and T. Spyropoulos, "Mobitrade: trading content in disruption tolerant networks," in *Proceedings of ACM CHANTS*, 2011.

[11] C. Boldrini, M. Conti, and A. Passarella, "Contentplace: social-aware data dissemination in opportunistic networks," in *Proceedings of ACM MSWiM*, 2008.

[12] A. Krifa, M. K. Sbai, C. Barakat, and T. Turletti, "Bithoc: A content sharing application for wireless ad hoc networks," in *Proceedings of IEEE PerCom*, 2009.

[13] G. Sollazzo, M. Musolesi, and C. Mascolo, "Taco-dtn: a time-aware content-based dissemination system for delay tolerant networks," in *Proceedings of ACM MobiOpp*, 2007.

[14] M. Motani, V. Srinivasan, and P. S. Nuggehalli, "Peoplenet: engineering a wireless virtual social network," in *Proceedings of ACM MobiCom*, 2005.

[15] F. Li and J. Wu, "MOPS: Providing content-based service in disruption-tolerant networks," in *Proceedings of IEEE ICDCS*, 2009.

[16] M. May, V. Lenders, G. Karlsson, and C. Wacha, "Wireless opportunistic podcasting: implementation and design tradeoffs," in *Proceedings of ACM CHANTS*, 2007.

[17] P. Costa, C. Mascolo, M. Musolesi, and G. P. Picco, "Socially-aware routing for publish-subscribe in delay-tolerant mobile ad hoc networks," *IEEE Journal on Selected Areas in Communications*, vol. 26, no. 5, pp. 748–760, 2008.

[18] W. Gao and G. Cao, "User-centric data dissemination in disruption tolerant networks," in *Proceedings of IEEE INFOCOM*, 2011.

[19] L. Buttyán and J. P. Hubaux, "Enforcing service availability in mobile ad-hoc wans," in *Proceedings of ACM MobiHoc*, 2000.

[20] G. Bigwood and T. Henderson, "Ironman: Using social networks to add incentives and reputation to opportunistic networks," in *Proceedings of IEEE SocialCom*, 2011.

[21] N. Li and S. K. Das, "Radon: Reputation-assisted data forwarding in opportunistic networks," in *Proceedings of ACM MobiOpp*, 2010.

[22] N. Li and S. K. Das, "A trust-based framework for data forwarding in opportunistic networks," *Ad Hoc Networks*, to appear, 2012.

[23] T. Ning, Z. Yang, X. Xie, and H. Wu, "Incentive-aware data dissemination in delay-tolerant mobile networks," in *Proceedings of IEEE SECON*, 2011.

[24] K. Srinivasan, S. Rajkumar, and P. Ramanathan, "Incentive schemes for data collaboration in disruption tolerant networks," in *Proceedings of IEEE GLOBECOM*, 2010.

[25] W. Gao, Q. Li, B. Zhao, and G. Cao, "Multicasting in delay tolerant networks: A social network perspective," in *Proceedings of ACM MobiHoc*, 2009.

[26] V. Conan, J. Leguay, and T. Friedman, "Characterizing pairwise inter-contact patterns in delay tolerant networks," in *Proceedings of ACM SenSys*, 2007.

[27] J. Scott, R. Gass, J. Crowcroft, P. Hui, C. Diot, and A. Chaintreau, "Crawdad data set cambridge/haggle (v. 2009-05-29)," 2009.

[28] N. Eagle, A. Pentland, and D. Lazer, "Inferring social network structure using mobile phone data," in *Proceedings of the National Academy of Sciences*, 2009.

[29] D. Qiu and R. Srikant, "Modeling and performance analysis of bittorrent-like peer-to-peer networks," in *ACM SIGCOMM Computer Communication Review*, vol. 34, pp. 367–378, ACM, 2004.

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